

# A Far Ultraviolet Archival Study of Cataclysmic Variables: I. *FUSE* and *HST*/STIS Spectra of the Exposed White Dwarf in Dwarf Nova Systems.<sup>1</sup>

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## ABSTRACT

We present a synthetic spectral analysis of Far Ultraviolet Spectroscopic Explorer (*FUSE*) and Hubble Space Telescope/Space Telescope Imaging Spectrograph (*HST*/STIS) spectra of 5 dwarf novae above and below the period gap during quiescence. We use our synthetic spectral code, including options for the treatment of the hydrogen quasi-molecular satellite lines (for low temperature stellar atmospheres), NLTE approximation (for high temperature stellar atmospheres), and for one system (RU Peg) we model the interstellar medium (ISM) molecular and atomic hydrogen lines. In all the systems presented here the FUV flux continuum is due to the WD. These spectra also exhibit some broad emission lines. In this work we confirm some of the previous FUV analysis results but we also present new results. For 4 systems we combine the *FUSE* and STIS spectra to cover a larger wavelength range and to improve the spectral fit. This work is part of our broader *HST* archival research program, in which we aim to provide accurate system parameters for cataclysmic variables above and below the period gap by combining *FUSE* and *HST* FUV spectra.

*Subject headings:* Stars: white Dwarfs, Stars: dwarf novae (SS Aur, EY Cyg, VW Hyi, RU Peg, EK TrA).

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## 1. Introduction

### 1.1. Dwarf Novae in Cataclysmic Variables

Cataclysmic variables (CVs) are short-period, semi-detached compact binaries in which the primary star, a white dwarf (WD), accretes matter and angular momentum from the secondary, a main-sequence star filling its Roche lobe (the mass donor) (Warner 1995). The matter is transferred by means of either an accretion disk around the WD, or an accretion column or curtain - when the WD has a strong magnetic field. Ongoing accretion at a low rate (quiescence) can be interrupted every few weeks to months by intense accretion (outburst) of days to weeks (a dwarf nova accretion event), and every few thousand years by a thermonuclear runaway explosion (TNR - the classical nova event, due to the ignition of the accreted layer of hydrogen-rich material). CVs are divided in sub-classes according to the duration, occurrence and amplitude of their outbursts. The two main types of CVs are Dwarf Nova systems (DNs; weakly- or non-magnetic disk systems found mostly in their quiescent state which lasts much longer than their outburst), and nova-like (NL) systems which form a less homogeneous class. NLs includes disk systems found mostly in their high state, intermediate polars (IPs; with a magnetically truncated inner disk), polars (devoid of disk due to the strong magnetic field of the WD), and other systems e.g. that never go into outburst or which cannot be classified as DNs (Warner 1995) (this includes the helium systems - AM CVn - with the shortest period). Dwarf nova systems includes the U Gem systems, the SU UMa systems, and the Z Cam systems. The U Gem systems are the typical DNs, i.e. those systems exhibiting normal DN outbursts; the SU UMas exhibit both normal DN outbursts, and superoutbursts, which are both longer in duration and higher in luminosity than normal DN outbursts; and the Z Cam systems have standstills where they remain in a state of intermediate optical brightness for a long time (here we adopt the classification according to Ritter & Kolb (2003)).

Interestingly enough, while the binary orbital period in CV systems ranges from a fraction of an hour (AM CVn systems) to about a day (e.g. GK Per), there is a gap in the orbital period between 2 and 3 hours where almost no systems are found (hereafter the “period gap”). For example U Gem and Z Cam DN systems are found above the period gap, while the SU UMa DN systems are found below the period gap. It is not known whether the systems are evolving from a longer period to a shorter period (across the gap) or whether the systems above the gap are altogether different from the systems below the gap.

The now widely accepted interpretation of the quiescence/outburst cycle is the disk instability model (DIM, Cannizzo (1998)). It is assumed that during the quiescent phase the matter in the disk is cold and neutral and the disk is optically thin because of its low density, while during outburst the matter in the disk is ionized and becomes optically thick as the mass accretion rate within the disk increases. The basic principle of the DIM theory depends heavily on the unknown viscosity parameter  $\alpha$  (Shakura & Sunyaev 1973) and on the mass transfer rate during the different phases. DNs, unlike other CVs, offer a fairly reliable estimate of their distances via the absolute magnitude at maximum versus orbital period relation for DNs found by Warner (1995). This

relationship is consistent with theory (Cannizzo 1998). The mass accretion rate within the disk has been taken from Patterson (1984), which is, however, only a first order estimate. In the last decade, the disk mass accretion rate of many systems has been deduced more accurately at given epochs of outburst or quiescence using spectral fitting techniques. The accretion rate is usually a function of time (especially during the outburst itself; and it is also a function of radius  $r$  due to wind-outflow from the disk) and, consequently, it is difficult to assess its time-averaged value accurately.

Recent advances in theory (Townesley & Bildsten 2004) have shown that the average mass accretion rate onto the WD in DNs can be deduced if one knows the mass of the accreting WD and its effective surface temperature during quiescence, therefore providing an additional and independent way to assess  $\dot{M}$  (or more precisely  $\dot{M}(r = R_*)$  - the mass accretion rate at one stellar radius  $R_*$  onto the stellar surface, which might be different than the mass accretion rate in the disk  $\dot{M}(r)$  at a radius  $r$  if there is an outflow from the disk:  $\partial\dot{M}/\partial r < 0$ ). Consequently, in order to put more constraints on the theories we need to know the properties (mainly the temperature and mass of the WD) of these systems above as well as below the period gap. There is, however, a critical shortage in knowledge of the WD properties (effective temperature  $T_{wd}$ , gravity  $\text{Log}(g)$ , projected rotational velocity  $V_{rot}\sin(i)$ , chemical abundances, accretion belts?) in DNs above the period gap. Thus, detailed comparisons of accreting WDs above and below the gap cannot be made.

For systems below the gap, with orbital periods near the period minimum (Warner 1995), the distribution of temperatures are centered at  $\sim 15,000\text{K}$  with only a narrow range identified at present. This distribution appears to manifest the effect of long term compressional heating at a time averaged accretion rate of  $2 \times 10^{-11} M_{\odot}\text{yr}^{-1}$  (Townesley and Bildsten 2002; Sion et al. 2003). It appears that WD  $T_{eff}$ 's for systems above the gap are higher than WD temperatures in systems below the gap, due to the systems above the gap having larger disks (with higher mass transfer rates) and more massive (somewhat earlier-type) secondaries. Some disks may remain optically thick even during quiescence so that the WDs are heated to a greater extent than systems below the gap. It is not yet known whether the WDs in systems above the gap are rotating more slowly than WDs in systems below the gap where presumably the CVs are older and with a longer history of angular momentum transfer via disk accretion. Thus far the only DNs above the gap whose WDs and disks/boundary layers have been analyzed with *FUSE*, *IUE* and *HST* have been Z Cam (Hartley et al. 2005), RX And (Sion et al. 2001; Sepinsky et al. 2002), U Gem (Sion et al. 1998; Long & Gilliland 1999; Froning et al. 2001), SS Aur (Sion et al. 2004a), EY Cyg (Sion et al. 2004b), RU Peg (Sion & Urban 2002; Sion et al. 2004a) and WW Cet (Godon et al. 2006b); a total of 2 Z Cam systems, 4 U Gem systems and the peculiar DN WW Ceti (although classified as a U Gem, others suggest it is a Z Cam).

Under our broader *HST* archival research we have started to secure accurate system parameters ( $\dot{M}$ ,  $i$ ,  $M_{wd}$ ,  $T_{eff}$ ,  $V_{rot}\sin(i)$ , chemical abundances, etc..) for CVs (DNs and NLs) above and below the period gap by fitting synthetic spectral models (WDs and accretion disks) to combined *FUSE*+*HST* spectra from the MAST archive. We have identified 25 CV systems for which the

*FUSE* and *HST* (STIS, FOS or GHRS) spectra match and can be combined. As a part of this *HST* archival research, we present in this paper the analysis of *HST*/STIS and (*FUSE*) archival spectra of 5 DNs during quiescence using synthetic stellar spectra together with the *FUSE* spectrum of RU Peg.

## 1.2. Five Dwarf Nova Systems

The five DNs are listed in Table 1 with their system parameters as follows: column (1) Name, (2) CV subtype, (3) reddening value  $E(B-V)$ , (4) distance, (5) orbital period in days, (6) orbital inclination in degrees, (7) spectral type of the secondary, (8) mass of the primary in solar masses, (9) mass of the secondary in solar masses, (10) apparent magnitude in outburst, and (11) apparent magnitude in quiescence. The references are listed below the table. Three systems are above the period gap: EY Cyg, SS Aur and RU Peg; and two systems are below the period gap: VW Hyi and EK TrA.

Among these 5 objects, 4 DNs in quiescence are directly from our *HST* archival program with matching *FUSE* and *HST*/STIS spectra: EY CYG, SS Aur, VW Hyi, and EK TrA. We supplement this study here with the analysis of RU Peg’s *FUSE* spectrum. For SS Aur, VW Hyi and EK TrA we assess the WD parameters by modeling for the first time for these 3 objects the combined *FUSE*+STIS spectra. For RU Peg’s *FUSE* spectrum, and EY Cyg’s combined *FUSE*+STIS spectrum we improve the fittings that were carried out previously.

For all the spectra we present here, we use the latest versions of the stellar model atmospheres and synthetic spectra codes (see section 3); this includes options for the treatment of the hydrogen molecular satellite lines (for modeling cooler WDs), and NLTE atmosphere models (for modeling hotter WDs). We also adopt the extinction values  $E(B-V)$  given in Bruch & Engel (1994) for the 5 objects and we deredden the spectra accordingly. For some systems we identify the ISM molecular absorption lines in the *FUSE* spectra; this greatly helps improve the fitting of the chemical abundances and WD’s temperature. RU Peg has stronger ISM absorption lines and, for this system only, we model the ISM atomic and molecular hydrogen opacities. For these 5 systems we obtain the temperature, projected rotational velocity and chemical abundances (of C, N, S and Si) of the exposed WD atmosphere. We also give upper and lower limits for the mass of the WD and the distance to the system.

## 2. The Archival Spectra

The observations log is presented in Table 2. From the *AAVSO* (American Association of Variable Stars Observers) data, we found that all the systems were in optical quiescence at the time of the observation (see the last column of Table 2). The STIS spectra of EY Cyg and SS Aur are snapshots (lasting 600-700s) with a lower resolution and S/N than the STIS spectra of VW Hyi

and EK TrA. With fluxes  $\leq 1 \times 10^{-14} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ , both EY Cyg and EK TrA are actually weak *FUSE* sources, and RU Peg (though with a *FUSE* flux ten times higher) is under-exposed with an exposure time of only 2800s.

## 2.1. The *FUSE* Archival Spectra

### 2.1.1. Processing the *FUSE* Data

*FUSE*'s optical system consists of four optical telescopes (mirrors), each connected to a Rowland spectrograph. The four diffraction gratings of the four spectrographs produce four independent spectra on two detectors. Two mirrors and two gratings are coated with SiC to provide wavelength coverage below 1020 Å, and the other two mirrors and gratings are coated with Al and LiF. The Al+LiF coating provides about twice the reflectivity of SiC at wavelengths >1050 Å, and very little reflectivity below 1020 Å. These are known as the SiC1, SiC2, LiF1 and LiF2 channels.

All the *FUSE* spectra presented here were obtained through the 30"x30" LWRS Large Square Aperture in TIME TAG mode. The data were processed with CalFUSE version 3.0.7 (Dixon et al. 2007), which automatically handles event bursts. Event bursts are short periods during an exposure when high count rates are registered on one or more detectors. The bursts exhibit a complex pattern on the detector, their cause, however, is yet unknown (it has been confirmed that they are not detector effects). The main change from previous versions of CalFUSE is that now the data are maintained as a photon list (the intermediate data file - IDF) throughout the pipeline. Bad photons are flagged but not discarded, so the user can examine, filter, and combine data without re-running the pipeline. A number of design changes enable the new pipeline to run faster and use less disk space than before. Processing time with CalFUSE has decreased by a factor of up to 10.

To process *FUSE* data, we follow the same procedure used previously for the analysis of other systems (such as WW Ceti, Godon et al. (2006b)); consequently we give only a short account of this procedure. The spectral regions covered by the spectral channels overlap, and these overlap regions are then used to renormalize the spectra in the SiC1, LiF2, and SiC2 channels to the flux in the LiF1 channel. We then produced a final spectrum that covers the full *FUSE* wavelength range 905 – 1187 Å. The low sensitivity portions of each channel were discarded. In most channels there exists a narrow dark stripe of decreased flux in the spectra running in the dispersion direction. This stripe has been known as the “worm” and it can attenuate as much as 50% of the incident light in the affected portions of the spectrum; - this is due to shadows thrown by the wires on the grid above the detector. Because of the temporal changes in the strength and position of the “worm”, CALFUSE cannot correct target fluxes for its presence. Therefore, we carried out a visual inspection of the *FUSE* channels to locate the worm and we *manually* discarded the portion of the spectrum affected by the worm. We combined the individual exposures and channels to create a time-averaged spectrum weighting the flux in each output datum by the exposure time and sensitivity of the input exposure and channel of origin.

### 2.1.2. The *FUSE* Lines

The *FUSE* spectra of DNs in quiescence exhibit mainly absorption lines from the WD itself, as the exposed WD is the main FUV component of the system. A second FUV component is sometimes present as a flat and featureless continuum contributing in the very short wavelengths of *FUSE* ( $\lambda < 970\text{\AA}$ ). This second component could be a hot region of the accretion disk (the inner disk) or the boundary/spread layer. Sharp absorption lines from circumstellar (or circumbinary) material and/or the ISM are also often seen and, if the system is a weak *FUSE* source, sharp emission lines from air glow (geo- and helio-coronal in origin) are present

Since the WD is the main component of the FUV spectra of DNs in quiescence, the main characteristic of the *FUSE* spectra is the broad  $\text{Ly}\beta$  absorption feature due to the gravity ( $\text{Log}(g) \approx 8$ ) and temperature ( $15,000\text{K} < T < 25,000\text{K}$ ) of the exposed WD (in the disk this feature is usually smoothed out due to velocity broadening, unless the disk is almost face-on). The other most common absorption features observed in the spectra of DNs WDs are due to C III ( $1175\text{\AA}$ ), C II ( $1066\text{\AA}$ ), Si III ( $\approx 1108\text{--}1114\text{\AA}$  and  $\approx 1140\text{--}1144\text{\AA}$ ), and N II ( $1085\text{\AA}$  when not contaminated by air glow). At higher temperatures ( $T > 25,000\text{K}$ ), as the continuum rises in the shorter wavelengths, the higher orders of the Lyman series also become visible; however, they become narrower. At these temperatures the Si IV ( $1073\text{\AA}$ ) absorption line starts to appear, and, as there is more flux in the shorter wavelengths, the C II ( $1010\text{\AA}$ ) absorption line also becomes visible. At still higher temperature ( $T > 50,000\text{K}$ ), the C II and Si III lines disappear, and the spectrum becomes dominated by high order ionization lines such as N IV ( $\approx 923\text{\AA}$ ), S VI ( $933.5$  &  $944.5\text{\AA}$ ), Si IV ( $1063$  &  $1073\text{\AA}$ ), Si IV ( $1066.6\text{\AA}$ ), and O IV ( $1067.8\text{\AA}$ ).

On top of the spectrum of the WD, broad emission lines are found in quiescent DN systems, usually the O VI doublet and C III ( $977\text{\AA}$  and  $1175\text{\AA}$ ). These, together with broad emission lines from N IV ( $\approx 923\text{\AA}$ ) and S VI ( $933.5$  &  $944.5\text{\AA}$ ) are often observed in nova-like systems (e.g. such as AE Aqr, V347 Pup, DW UMa, see the MAST *FUSE* archives) and are not usually present in low-inclination DN systems in quiescence. This implies that the gas could possibly be heated by a shock (e.g. in the boundary layer) and the broadening and variation of the lines suggests they are originating in the disk. This scenario has recently been supported by Kromer et al. (2007) who for the first time modeled the broad H and He emission lines *ab initio* as irradiation of the inner disk by the hot boundary layer and/or white dwarf. One fully expects that the metallic emission lines form in the same way. The DN system here that exhibits the strongest emission lines is EK TrA ( $i=58^\circ$ ). RU Peg ( $i=33^\circ$ ) does have some strong emission lines too, but lacks a STIS spectrum for complete comparison; however, its *IUE* spectrum clearly show strong emission lines such as C IV ( $1550\text{\AA}$ ) and Si IV ( $1400\text{\AA}$ ).

The *FUSE* spectra of the DN systems (and CVs in general) often show some ISM molecular hydrogen absorption, which appears as sharp lines at almost equal intervals ( $12\text{\AA}$ ) starting at wavelengths around  $1110\text{\AA}$  and continuing towards shorter wavelengths all the way down to the

hydrogen cut-off around  $915\text{\AA}$ . In the affected *FUSE* spectra, we identified the most prominent molecular hydrogen absorption lines by their band (Werner or Lyman), upper vibrational level (1-16), and rotational transition (R, P, or Q) with lower rotational state ( $J=1,2,3$ ).

## 2.2. The *HST*/STIS Archival Spectra

### 2.2.1. Processing the *HST*/STIS Archival Data

All the STIS spectra were processed with CALSTIS version 2.19. Except for the spectrum of EK TrA (obtained in TIME TAG operation mode), all the spectra were obtained in ACCUM operation mode. All the STIS spectra used the FUV MAMA detector and all were centered on the wavelength  $1425\text{\AA}$ . The STIS snapshots (with an exposure time of about 600-700s, for EY Cyg and SS Aur) were obtained through the  $52\times 0.2$  aperture using the G140L optical element. These snapshots consist of one spectrum. The STIS spectra of VW Hyi and EK TrA (with an exposure time of 4,000s and above) were obtained through the  $0.2\times 0.2$  aperture using the E140M optical elements, and with 42 echelle spectra each, are of a much higher resolution than the snapshots. Towards the longer wavelengths, the echelle spectra do not overlap and five gaps are apparent around  $\lambda \approx 1634\text{\AA}$ ,  $1653\text{\AA}$ ,  $1672\text{\AA}$ ,  $1691\text{\AA}$ , and  $1710\text{\AA}$ .

### 2.2.2. The *HST*/STIS Lines

The STIS spectra of quiescent DNs are also dominated by the WD and their main characteristic is the broad  $\text{Ly}\alpha$  absorption feature at  $\approx 1216\text{\AA}$ . The other very common absorption lines are the carbon lines C I ( $1266\text{\AA}$ ,  $1561\text{\AA}$ ,  $1657\text{\AA}$ ), C II ( $1335\text{\AA}$ ), and C III ( $1175\text{\AA}$ ); and the silicon lines Si II ( $1260\text{\AA}$ ,  $1300\text{\AA}$ ,  $1530\text{\AA}$ ), Si III ( $1300\text{\AA}$ ), and Si IV ( $1400\text{\AA}$ ).

The *HST*/STIS spectrum also exhibits some broad emission lines. The most prominent ones are C III ( $1175\text{\AA}$ ), C IV ( $1550\text{\AA}$ ), Si III ( $1206\text{\AA}$ ), N V ( $1240\text{\AA}$ ), He II ( $1640\text{\AA}$  Balmer  $\alpha$ ), and Si IV ( $1400\text{\AA}$ ). With their broad emission lines, both the *FUSE* and *HST*/STIS spectra show evidence of hot gas.

## 2.3. Preparation of the Spectra

For four objects (EY Cyg, SS Aur, VW Hyi and EK TrA) we wish to combine the *FUSE* spectrum with the *HST*/STIS spectrum in order to have a larger wavelength coverage and improve the synthetic spectral modeling.

However, for each object, before combining the *FUSE* spectrum with the STIS spectrum we must make sure that (i) the system was observed in the same (high or low) state; (ii) the shape of

the spectra (continuum and lines) is similar (if the spectra are not too noisy); (iii) the flux level in the *FUSE* and *HST*/STIS spectra do not differ more than about 50% (*FUSE* and *HST*/STIS are very different instruments, we do not expect their flux level to match exactly); (iv) for long period systems for which only short exposure time spectra exist, the *FUSE* and STIS spectra have most probably been obtained at a different binary orbital phase and it is not clear one can combine such spectra. We address these points here in detail as follows.

(i) The observations listed here were not coordinated and consequently some were carried out during early quiescence while others were carried out in late quiescence. For EY Cyg, the outburst recurrence time is believed to be about 2000 days and the *FUSE* and STIS spectra were obtained in deep quiescence. EK TrA has also a long outburst recurrence time and it was observed in deep quiescence (45 days and 155 days after outburst). For SS Aur, both spectra were obtained about a month into quiescence. For VW Hyi the *FUSE* spectrum was obtained 11 days into quiescence while the main STIS spectrum was obtained 15 days into quiescence (we discuss VW Hyi in some more detail in the results section).

(ii) For all the systems, a visual analysis shows that the shape of the continuum and lines is similar in the *FUSE* and STIS spectra.

(iii) Only 2 systems (EY Cyg and SS Aur) have *FUSE* and STIS flux levels that do not match exactly. For EY Cyg the STIS spectrum had to be multiplied by 1.5 to match the flux level of the continuum in the *FUSE* spectrum, while for SS Aur it was multiplied by 0.93. At temperatures of about 25,000K a change of 2,000K can produce a change of 50 percent in the flux; the accuracy of the temperature we obtained for EY Cyg is therefore of this order (i.e.  $\pm 2,000\text{K}$ ).

(iv) Since the systems were observed in quiescence, we expect mainly to see the exposed WD with basically no contribution or occultation from the accretion disk (none of these systems is eclipsing). The spectra, whether observed at a given phase or averaged over an entire orbit, should not differ significantly. Only for spectra with a high S/N ratio and a high inclination do we expect the absorption and emission lines to exhibit some red- or blue- shift if they were obtained at a given orbital phase, while the orbit-averaged spectra will have broader absorption and emission features.

Except for RU Peg, all the *FUSE* spectra exposure times cover a significant fraction of the orbital period (and in some cases several periods); therefore, the *FUSE* spectra are averaged over a significantly large fraction of the orbit. The STIS spectra of VW Hyi and EK TrA are also averaged over the orbit, and for these two systems one can therefore combine the *FUSE* and STIS spectra.

The STIS snapshots of EY Cyg and SS Aur are very short (less than 1ksec) and were taken at a particular orbital phase. One might therefore argue that the STIS and *FUSE* spectra of EY Cyg and SS Aur cannot be combined because of that. However, for both EY Cyg and SS Aur, they fit except that the absorption lines in the STIS range are not as deep as in the *FUSE* range. The effect of observing the systems at a particular orbital phase is not very pronounced, and this might be due to the lower resolution of the STIS snapshots (in comparison to VW Hyi and EK TrA's STIS spectra) and the moderate inclination of EY Cyg and SS Aur. Therefore, for EY Cyg and



SS Aur, we also combine the *FUSE* and STIS spectra without concern about the orbital phase.

The only object for which we find a significant shift in the lines is the long period system RU Peg, for which we only have a *FUSE* spectrum of 2,800s.

Finally, we deredden the spectra according to the E(B-V) values given in Verbunt (1987); La Dous (1991); Bruch & Engel (1994).

### 3. Spectral Modeling

#### 3.1. The Synthetic Stellar Spectral Codes

We create model spectra for high-gravity stellar atmospheres using codes TLUSTY and SYNSPEC<sup>1</sup> (Hubeny 1988; Hubeny & Lanz 1995). Atmospheric structure was computed (using TLUSTY) assuming a H-He LTE atmosphere; the other species were added in the spectrum synthesis stage using SYNSPEC. For hot models (say  $T > 50,000\text{K}$ ) we switched the approximate NLTE treatment option in SYNSPEC (this allows to consider and approximate NLTE treatment even for LTE models generated by TLUSTY). We generate photospheric models with effective temperatures ranging from 12,000K to 75,000K in increments of about 10 percent (e.g. 1,000K for  $T \approx 15,000\text{K}$  and 5,000K for  $T \approx 70,000\text{K}$ ). We chose values of  $\text{Log}(g)$  ranging between 7.5 and 9.5 for consistency with the observed mass. We also varied the stellar rotational velocity  $V_{\text{rot}} \sin(i)$  from  $100\text{km s}^{-1}$  to  $1000\text{km s}^{-1}$  in steps of  $100\text{km s}^{-1}$  (or smaller if needed). In order to try and fit the absorption features of the spectrum, we also vary the chemical abundances of C, N, S and Si. For any WD mass there is a corresponding radius, or equivalently one single value of  $\text{Log}(g)$  (e.g. see the mass radius relation from Hamada & Salpeter (1961) or see Wood (1990); Panei et al. (2000) for different composition and non-zero temperature WDs).

Our suite of stellar spectra generator codes has been implemented and includes also the treatment of the quasi-molecular satellite Lyman lines. The satellite hydrogen lines appear as strong absorption features near 1400 and 1600Å ( $\text{Ly}\alpha$ , in the IUE and STIS range; Koester et al. (1985); Nelan & Wegner (1985)) and are somewhat weaker near 1060 and 1078Å ( $\text{Ly}\beta$ , in the *FUSE* range; e.g. Dupuis et al. (2006)). Following Dupuis et al. (2003, 2006), we used opacity tables computed by Allard et al. (1998, 1994, 2004a) to take into account the quasi-molecular satellite line opacities of  $\text{H}_2$  and  $\text{H}_2^+$  for  $\text{Ly}\alpha$ ,  $\text{Ly}\beta$ , and  $\text{Ly}\gamma$ . The quasi-molecular lines are expected to appear when the temperature of the WD is  $\approx 20,000\text{K}$  or lower, though the gravity, pressure and magnetic field of the WD can also play a role in the formation of these lines (larger electronic density will favor recombination, see e.g. Dupuis et al. (2003); Gänsicke et al. (2006) for a more complete discussion).

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<sup>1</sup> <http://nova.astro.umd.edu>; TLUSTY version 200, SYNSPEC version 48

### 3.2. Modeling the ISM Hydrogen Absorption Lines

For all the systems showing ISM atomic and molecular hydrogen absorption lines, we identify these lines in the figures to avoid confusing them with the WD lines. For RU Peg, however, some ISM lines are deep and broad and we decided to model them, especially since some of the WD lines (such as S IV  $\lambda\lambda 1062.6$  &  $1073$ ) are located at almost the same wavelengths.

For RU Peg only, we model the ISM hydrogen absorption lines to assess the atomic and molecular column densities. This enables us to differentiate between the WD lines and the ISM lines, and helps improve the WD spectral fit. The ISM spectra models are generated using a program developed by P.E. Barrett. This program uses a custom spectral fitting package to estimate the temperature and density of the interstellar absorption lines of atomic and molecular hydrogen. The ISM model assumes that the temperature, bulk velocity, and turbulent velocity of the medium are the same for all atomic and molecular species, whereas the densities of atomic and molecular hydrogen, and the ratios of deuterium to hydrogen and metals (including helium) to hydrogen can be adjusted independently. The model uses atomic data of Morton (2000, 2003) and molecular data of Abgrall et al. (2000). The optical depth calculations of molecular hydrogen have been checked against those of McCandliss (2003).

The ratios of metals to hydrogen and deuterium to hydrogen are fixed at 0 and  $2 \times 10^{-5}$ , respectively, because of the low signal-to-noise ratio data. The wings of the atomic lines are used to estimate the density of atomic hydrogen and the depth of the unsaturated molecular lines for molecular hydrogen. The temperature and turbulent velocity of the medium are primarily determined from the lines of molecular hydrogen when the ISM temperatures are  $< 250\text{K}$ .

The ISM absorption features are best modeled and displayed when the theoretical ISM model (transmission values) is combined with a synthetic spectrum for the object (namely a WD synthetic spectrum).

### 3.3. Synthetic Spectral Model Fitting

Before carrying out a synthetic spectral fit of the spectra, we masked portions of the spectra with strong emission lines, strong ISM molecular absorption lines, detector noise and air glow. These regions of the spectra are somewhat different for each object and are not included in the fitting. The regions excluded from the fit are in blue in Figures 1, 3, 5, 7, and 10. The excluded ISM quasi-molecular absorption lines are marked with vertical labels in figures 2, 4, and 9. For RU Peg, we model the ISM absorption features and the WD separately; namely, we also mask the ISM absorption features when we model the WD.

After having generated grids of models for each target, we use FIT (Press et al. 1992), a  $\chi^2$  minimization routine, to compute the reduced  $\chi^2_\nu$  ( $\chi^2$  per number of degrees of freedom) and scale factor values for each model fit. While we use a  $\chi^2$  minimization technique, we do not blindly

select the least  $\chi^2$  models, but we examine the models that best fit some of the features such as absorption lines (see the fit to the *FUSE* spectrum alone) and, when possible, the slope of the wings of the broad Lyman absorption features. We also select the models that are in agreement with the known distance of the system.

However, in the model fitting, for a given WD mass and radius, the resulting temperature depends mainly on the shape of the spectrum in the *FUSE* range. The flux level at 1000Å (between Ly $\delta$  and Ly $\gamma$ ) is close to zero for temperatures below 18,000K, at 30,000K it is about 50% of the continuum level at 1100Å and it reaches 100% for  $T > 45,000\text{K}$ . At higher temperature ( $T > 50,000\text{K}$ ) the spectrum becomes pretty flat and there is not much difference in the shape of the spectrum between (say) a 50,000K and a 80,000K model. When fitting the shape of the spectrum in such a manner, an accuracy of about 500-1,000K is obtained, due to the S/N. In theory, a fine tuning of the temperature (say to an accuracy of about  $\pm 50\text{K}$ ) can be carried out by fitting the flux levels such that the distance to the system (if known) is obtained accurately. However, the fitting to the distance depends strongly on the radius (and therefore the mass) of the WD. In all the systems presented here the error on the measured mass of the WD is so large (see Table 1) that it produces an error in the temperature much larger than 1,000K. This is because the Ly $\alpha$  and Ly $\beta$  profiles depend on both temperature and gravity. For example Gänsicke et al. (2001) derived a best fit temperature for EK Tra  $T_{eff} \approx 2360 \times \text{Log}(g) - 95$ , where  $g$  is the (unknown) surface gravity of the WD ( $7.0 < \text{Log}(g) < 9.0$ ). Additional errors are further introduced as the distance and reddening are rarely known accurately, therefore increasing significantly the inaccuracy of assessing the temperature by scaling the synthetic flux to the observed flux. For these, we decided to fit the temperature of each model, based on the shape of the *FUSE* spectrum in the shorter wavelengths, for a temperature accuracy of only about 5%, namely accurate to within 500K for  $T < 20,000\text{K}$ ; 1,000K for  $20,000\text{K} < T < 35,000\text{K}$ ; and 2,000K for  $T > 40,000\text{K}$  (see the Results section). While the error in temperature is only 500K for a 18,000K model and 2,000K for a 50,000K model, the relative error  $\Delta T/T$  is the same for all the models.

For all models we first tried fitting solar abundance models and then tried changing the abundances of some species to improve the spectral fit. In particular, for each system we fit obvious absorption features which can determine the abundance of some specific element (C, Si, S, N). For example, the C II ( $\approx 1065 \text{ \AA}$ ), the Si III ( $\approx 1110 \text{ \AA}$ ) and the Si-C blend ( $\approx 1138\text{-}1146 \text{ \AA}$ ) are the main absorption features in the *FUSE* range of a  $T=20,000\text{K}$  WD that help assess the Si and the C abundances (these are discussed in detail for each system in the next section).

The WD rotation ( $V_{rot} \sin(i)$ ) rate is determined by fitting the WD model to the spectrum while paying careful attention to the line profiles in the *FUSE* portion of the combined spectrum. We did not carry out separate fits to individual lines but rather tried to fit the lines and continuum in the same fit while paying careful attention to the absorption lines.

It is important to note that, in the modeling, the depth of the absorption features depends not only on the abundances but also on the rotational velocity. Increasing the rotational velocity

decreases the depth of the absorption features, but broadens the wings - the net effect being that higher metal abundances result with faster rotational velocity. With sufficiently high S/N data, it becomes possible to assess the rotational velocity and abundances independently.

## 4. Results and Discussion

All the results are presented in Table 5. For some systems for which the mass of the WD is relatively unknown, we list more than one optimized fit result, assuming different values of  $\text{Log}(g)$  (i.e. for each value of  $\text{Log}(g)$  we find an optimized fit). In the first column we list the name of the system; in the second column the assumed surface gravity on a logarithmic scale  $\text{Log}(g)$  (where it is understood that  $\text{Log}$  is the logarithm to the base 10 - as opposed to  $\log$  which denotes the logarithm to the base  $e$ ) in cgs units; in column (3) we list the effective surface temperature we obtained for the WD; in column (4) we list the projected rotational velocity which was obtained when matching the stellar absorption lines; in columns (5), (6), (7) and (8) we list the abundances of Carbon, Silicon, Nitrogen and Sulfur (respectively) in solar units; in column (9) we list the distance we obtained from the fitting; in column (10) we list the parameter by which the STIS flux had to be multiplied to match the *FUSE* flux; in column (11) we give the  $\chi^2_\nu$  value; and in column (12) we indicate the number of the figure displaying the model fit.

### 4.1. EY Cygni

EY Cygni is a peculiar long period U Geminorum-type of DN, with a very massive accreting WD ( $M_1 = 1.26M_\odot$  or possibly larger), an outburst amplitude of 4.1 magnitude with a recurrence time of 2000 days, and an orbital period of 11.0238 hrs (Smith et al. 1997; Costero et al. 1998; Tovmassian et al. 2002; Costero et al. 2004).  $\text{H}\alpha$  and  $\text{S II}$  ground-based imaging has revealed it is associated with a non-homogeneous shell with a size of about 25arcsec (Tovmassian et al. 2002; Sion et al. 2004b). It is possible that this shell is the result of a recent nova explosion. The spectral type of the secondary is not certain, it is believed to be a K5V to M0V star, from which the lower limit of the distance to EY Cyg has been inferred to be at least 250pc. Since EY Cyg is not embedded in the background Cygnus superbubble (Bochkarev & Sitnik 1985), the upper limit for its distance is 700pc. An additional characteristic which makes EY Cyg a peculiar DN is its anomalous N V/C IV ratio. Winter & Sion (2001) first reported a very strong N V emission and a very weak (or absent) C IV, which is atypical of most DNs in which C IV is usually the most prominent and common emission line in their FUV spectra. More recently Gänsicke et al. (2003) reported an analysis of *HST*/STIS snapshots of 4 CVs (including EY Cyg) with anomalously large N V/C IV line flux ratios, similar to those observed in AE Aqr. So far 10 systems have been identified with such an anomalous N V/C IV ratio.

EY Cyg is an extremely weak *FUSE* source and the spectrum is therefore very noisy, which

is the reason we binned its *FUSE* spectrum at  $0.5\text{\AA}$  for the fitting (Figure 1). The STIS snapshot spectrum was binned at the default value of  $0.58\text{\AA}$ . Consequently the relative weight of the *STIS* spectrum is about twice as large as that of the *FUSE* spectrum. In preparation for the model fitting we had to multiply the STIS flux by 1.5 to match the *FUSE* flux level; this change of 50% in flux corresponds to a  $(0.5)^{\frac{1}{4}} \approx 10\%$  in the value of  $T$ . Therefore, the relative error in temperature in our spectral modeling of the combined *FUSE*+*STIS* spectrum of EY Cyg is of the order of  $\sim 0.1$  *ab initio*. Since the distance to the system is relatively unknown, there is no restriction on the flux level to minimize the number of best fits to one in the  $\text{Log}(g) - T_{\text{eff}}$  parameter space. Therefore, we restricted the modeling assuming only two different values for the mass of the WD. Because of the extremely large WD mass of the system (which within the margin of error well exceeds the Chandrasekhar mass limit for a WD) we ran models assuming  $\text{Log}(g) = 9.0$  (corresponding to  $M_{\text{wd}} = 1.21M_{\odot}$ ) and  $\text{Log}(g) = 9.5$  (corresponding to  $M_{\text{wd}} = 1.35M_{\odot}$ ).

Within the range of the temperature error (10%) the best fit models spread between about  $T=27,000\text{K}$  and  $T=33,000\text{K}$ . However, the high temperature ( $T > 32,000\text{K}$ ) models do not produce enough flux in the longer wavelengths of STIS, while the lower temperature ( $T < 28,000\text{K}$ ) models do not have enough flux in the shorter wavelengths of the *FUSE* portion of the spectrum. Because of that we rejected the  $T = 27,000\text{K}$  and  $T = 33,000\text{K}$  models. In addition, in the observed STIS spectrum the bottom of the  $\text{Ly}\alpha$  does not go to zero and this corresponds to models with  $T \sim 30,000\text{K}$  and higher. Because of the difference in fluxes between STIS and *FUSE* we decided to check how the results would change if we fit the spectra separately. We found that the STIS spectrum gave the same temperature, however with a distance about 20 percent larger as the main driving elements in choosing the best fit model were the same, namely: the  $\text{Ly}\alpha$  profile and the longer wavelengths of STIS. Fitting the *FUSE* spectrum alone gave a temperature about 2,000K higher than for the combined spectrum. We therefore inferred for EY Cyg  $T = 30,000\text{K} \pm 2,000\text{K}$  assuming  $\text{Log}(g) = 9.0$ . The 2,000K error in  $T$  produces an error of  $\pm 60\text{pc}$  in the distance as listed in Table 5. This 30,000K model is shown in Figure 1. In Figure 2 the 30,000K WD model assuming  $\text{Log}(g) = 9.0$  is shown with the *FUSE* spectrum binned here at  $0.1\text{\AA}$  to show the sharp emission and absorption lines.

We also checked how the inclusion of the quasi-molecular hydrogen affects the result and found that it does not improve the fits.

Next, we assume  $\text{Log}(g) = 9.5$  to check the effect of larger WD mass. Using the same considerations as before we found that the best fit models range between 30,000K and 34,000K, or about 2,000K higher than the  $\text{Log}(g) = 9.0$  models.

The projected rotational velocity we obtained for all the models is relatively low:  $100\text{km s}^{-1}$ . We confirm the anomalously low Carbon abundance, namely we found that the best Carbon line fits are obtained for abundances ranging between 0.01 and 0.05 solar. The low carbon abundance was set to match the *FUSE* absorption features of C III 1175  $\text{\AA}$ , C II 1066  $\text{\AA}$ , and C I-C III at 1128 and 1140  $\text{\AA}$ . There is also a complete absence of C III emission at 977 $\text{\AA}$  and 1175 $\text{\AA}$ , and C IV emission at

1550Å . There is a strong and broad N V 1240 Å emission line. The Nitrogen abundance ( $2\times$  solar) was obtained by fitting the N I (1135Å), N II (1185Å), and N III (1189Å) lines. However, these lines are not very pronounced and are affected by air glow emission. The Sulfur abundance ( $6\times$  solar) was obtained by fitting the S IV (1073Å) and S I (1097Å) lines. The Silicon abundance ( $0.6\times$  solar) was obtained by fitting the Si IV (1125Å), and Si III (1140-1145Å) lines.

Sion et al. (2004b) modeled the combined *HST*/STIS and *FUSE* spectra of EY Cygni. Despite the noisy, weak *FUSE* spectrum, they managed to obtain two possible solutions which in a statistical ( $\chi^2_\nu$ ) sense differ little from each other. If the combined FUV spectra was due to a single temperature white dwarf alone, then for their adopted mass of  $1.2M_\odot$  (assuming  $\log(g) = 9$ ) with no interstellar reddening (see below), then the WD has  $T_{eff} = 24,000\text{K}$ . However, the combined *FUSE* plus STIS spectra also yielded a similar statistical fit if a two-temperature white dwarf model was applied to the data. This fit corresponded to a cooler, slowly rotating WD photosphere ( $T_{eff} = 22,000\text{K}$ ) with the second temperature ( $T_{eff} = 36,000\text{K}$ ) representing a putative hot, rapidly rotating, equatorial accretion zone (an accretion belt). We note here that their noisy *FUSE* spectrum showed a sharp increase in flux extending even beyond the Lyman limit. This extra flux is an artifact of the CalFUSE background subtraction and, therefore, in the present work we process the *FUSE* data with latest (and final) version of CalFUSE (v3.2) which lowered the flux at wavelengths  $\lambda < 950\text{\AA}$ , removing the shortward flux excess. The new combined *HST*/STIS plus reprocessed *FUSE* data is fit in the present paper with the *FUSE* spectral region shortward of 950Å masked in the fitting.

Our single WD component best fit, assuming  $\log(g) = 9.0$ , has  $T_{eff} = 30,000\text{K}$ , with a distance  $d \sim 500\text{pc}$ ; and assuming  $\log(g) = 9.5$  we found a WD temperature of  $32,000\text{K}$  with a distance of  $\sim 300\text{pc}$ . EY Cyg does not show any sign of quasi-molecular satellite lines, and this is consistent with our higher temperature model (see the Discussion section), and no need to add a second component since this component was driven by the flux excess which the re-processing removed.

## 4.2. SS Aurigae

SS Aur is a U Gem type DN with an orbital period  $P_{orb} = 4.3872$  hrs (Shafter & Harkness 1986), a WD mass  $M_{wd} = 1.08 \pm 0.40 M_\odot$ , a secondary mass  $M_2 = 0.39 \pm 0.02 M_\odot$ , and a system inclination  $i = 38^\circ \pm 16^\circ$  (Shafter 1983). SS Aur has an *HST* FGS parallax measurement of 497 mas (Harrison et al. 1999) giving a distance of 201pc.

Lake & Sion (2001) analyzed the IUE archival spectra of SS Aur; their best-fit model photosphere has  $T_{eff} = 30,000\text{K}$ ,  $\log(g) = 8.0$ , and solar composition abundances; while the best-fit accretion disk model has  $M_{wd} = 1.0 M_\odot$ ,  $i = 41^\circ$ , and  $\dot{M} = 10^{-10} M_\odot \text{yr}^{-1}$ .

Using a newly available Hubble FGS parallax, Lake & Sion (2001) showed for the first time

that the FUV flux of SS Aur during quiescence was dominated by, if not provided entirely by, a hot WD, not an accretion disk. This was something of a milestone because the prevailing view was that the underlying degenerate was detected in the FUV only in those dwarf novae which clearly revealed the broad Ly $\alpha$  profile of a WD, namely U Gem, VW Hyi and WZ Sge.

More recently Sion et al. (2004a) analyzed the *FUSE* spectrum of the system. Their best fit model is a 27,000K WD contributing 73% of the flux with a hot belt (48,000K) contributing the remaining 27% of the flux, with a corresponding distance of 267pc. However, a single WD component also gives a good fit with a temperature  $T_{wd}$ =33,000K and a distance of 303pc. They also suggested that the absence of the C III (1175Å) absorption line might be a sign of composition deficit in carbon. It is important to note here that in these previous studies the spectra of SS Aur were not dereddened.

The STIS spectrum of SS Aur was obtained as part of a snapshot program (Gänsicke et al. 2003) and the single STIS spectrum is being analyzed also in Sion et al. (2008). Here, we analyzed the combined *FUSE*+STIS spectrum of SS Aur which we dereddened assuming  $E(B-V)$ =0.08 (Bruch & Engel 1994). The *FUSE* spectrum of SS Aur was obtained 28 days after outburst, while the STIS spectrum was obtained 34 days after outburst. The fit was carried out with a binning of 0.2 Å in the *FUSE* spectrum and 0.58 Å in the *STIS* spectrum, consequently the relative weight of the *FUSE* spectrum is about 50% larger than that of the *STIS* spectrum.

The best fit model for a  $\approx 1.1M_{\odot}$  ( $Log(g) = 8.71$ ) mass WD and a distance of 200pc gives a temperature of 31,000K, solar abundances, a rotational velocity of 400km/s and  $\chi^2_{\nu}$ =1.476. This fit is the best when fitting the flux level while keeping the distance and radius of the star fixed. If we relax the restriction on the distance, the best fit model with  $Log(g) = 8.71$  gives a temperature of 33,000K, a distance of about 240pc and a slightly lower  $\chi^2_{\nu}$  (1.472). The difference in the values of the  $\chi^2_{\nu}$  between the 31,000K and the 33,000K models is not significant. However, it is this discrepancy between the apparent temperature of the WD and its flux that has led to the adoption of second model components in other CVs. However, the WD mass of SS Aur is given with a large error ( $\pm 0.4M_{\odot}$ ). We, therefore, computed more models with  $Log(g) = 8.31$  and 8.93. The  $Log(g) = 8.31$  model, for a distance of 200pc gave a temperature of 27,000K, while the lowest  $\chi^2_{\nu}$  best fit model for that value of  $Log(g)$  gave a temperature of 30,000K and a distance of 254pc. For the  $Log(g) = 8.93$  model, the distance of 200pc is achieved with a temperature of 34,000K. This model, however, is also the lowest  $\chi^2_{\nu}$  best fit model for that value of  $Log(g)$  with the least  $\chi^2_{\nu}$  of all (1.471).

A model fit to the STIS spectrum alone of SS Aur (which was carried out in (Sion et al. 2008)) gave the same results, namely a 34,000K WD assuming  $Log(g) = 8.8$ . The only difference with our modeling is that the STIS spectrum in Sion et al. (2008) was NOT normalized to the *FUSE* spectrum, which explain the slight difference in the value of  $Log(g)$ . We then ran a model to fit the *FUSE* spectrum alone and found total agreement with the *FUSE*+STIS spectral fits, namely that the best fit model is again a T=34,000K WD, spinning at 400km/sec with solar abundances,

for  $\text{Log}(g) = 8.93$  and a distance of 200pc. We therefore adopted this model as the best model fit for SS Aur, as it is produced within the margin of error of the WD mass and it is the simplest (one component) model possible. We do not see any need to add a second FUV component in the spectral modeling of SS Aur. The presence of a second (flat and featureless) component to the spectrum of SS Aur has not been detected as in the case of VW Hyi, and in the present work we restrict our modeling to a single WD component. The  $\text{Log}(g) = 8.93$  best fit model with a temperature of 34,000K is shown in Figure 3. In Figure 4, we show the same model superposed to the *FUSE* spectrum binned at 0.1 Å.

Usually C II (1066Å) and C III (1175Å) are in absorption in a 30,000K WD stellar atmosphere while C III (1175Å) and C III (977Å) can show emission originating in a hot second component (e.g. thin disk, accretion column, BL). From Figure 4, we see C II (1066Å and 1010Å) is in absorption while C III (977Å) is in emission. C III (1175Å) on the other hand does not show any sign of absorption nor emission (it could be a superposition of absorption and emission). We therefore decided to fit the carbon abundances by fitting the C II lines; achieved by simply assuming solar abundances (we note that if we assume a low carbon abundance to fit the C III 1175 feature, then the C II absorption features at 1010Å and 1066Å are not fitted). We do not find evidence that the WD is deficient in carbon as is the case for EY Cyg, especially since the C IV (1550Å) is in strong emission in the STIS snapshot.

In the present work, we have improved the line identifications and the fitting in the shorter wavelengths without the need for a second component. The second component (Sion et al. 2004a) gives too much flux in the short wavelengths. The distance we obtained is in very good agreement with the distance estimated from the parallax, which is smaller by 50% than the distance obtained in Sion et al. (2004a) (a result of our dereddening).

### 4.3. VW Hydri

VW Hyi is a key system for understanding DNs in general. It is one of the closest (Warner 1987, placed it at 65 pc) and brightest examples of an SU UMa-type DN. It lies along a line of sight with a low interstellar column (Polidan, Mauche & Wade 1990, estimated the H I column density to be  $\approx 6 \times 10^{17} \text{ cm}^{-2}$ ), which has permitted study of VW Hyi in nearly all wavelength ranges, including detection in the usually opaque extreme ultraviolet (Mauche 1996). For these reasons, it is one of the best-studied systems. Coherent and quasi-coherent soft X-ray oscillations have been detected, and its X-ray luminosity has been found to be unexpectedly low (Belloni et al. 1991; Mauche et al. 1991). Its boundary layer (BL) has been shown to emit most of its energy in the FUV band Pandel et al. (2003, 2005); Godon & Sion (2005). VW Hyi is near the lower edge of the CV period gap, with an orbital period of 1.78 hrs and a quiescent optical magnitude of 13.8. It is a member of the SU UMa class of DNs, which undergo both normal DN outbursts and superoutbursts. The normal outbursts last 1-3 days and occur every 20-30 days, with peak visual magnitude of 9.5. The superoutbursts last 10-15 days And occur every 5-6 months, with



peak visual magnitude reaching 8.5. The mass of the accreting WD was estimated to be  $0.63 M_{\odot}$  (Schoembs & Vogt 1981), but more recently a gravitational redshift determination yielded a larger mass  $M_{wd} = 0.86 M_{\odot}$  (Sion et al. 1997). The inclination of the system is  $\approx 60^{\circ}$  (Huang et al. 1996a,b).

VW Hyi was first observed at UV wavelengths with *IUE*. Based on observations of VW Hyi in quiescence, which showed a broad absorption profile centered on Lyman  $\alpha$ , Mateo & Szkody (1984) argued that UV light from the system was dominated by the WD with  $T_{eff} = 18,000 \pm 2,000$  K (for  $\log(g) = 8$ ). Much higher S/N spectra were obtained with *HST*. In particular, Sion et al. (1995a) found the WD temperature to be 22,000K, the first metal abundances, with evidence of CNO processing of material in the WD photosphere. They also derived the first rotational velocity for a WD in a CV using the GHRS G160M spectrum of VW Hyi (Sion et al. 1995b) thus showing that weak boundary layer emission from some CVs could not be explained by their WDs rotating near Keplerian speeds. Sion et al. (1996, 2001) concluded that the temperature of the WD varied by at least 2000K depending on the time since the outburst. They also presented evidence for rapidly rotating "accretion belt" in the system. The accretion belt was to be understood physically as a region of the WD surface spun up by accreting material with Keplerian velocities. Furthermore, Sion et al. (1997), using the GHRS on *HST*, measured the gravitational redshift of the WD and concluded that the mass of the WD was  $0.86^{+0.18}_{-0.32} M_{\odot}$  and that the rotation rate of the WD was  $\sim 400 \text{ km s}^{-1}$ . All of these observations were limited to a wavelength range longward of about 1150 Å. However, an 820-1840 Å spectrum of VW Hyi was obtained using the Hopkins Ultraviolet Telescope (HUT). Long et al. (1996) found that the HUT spectrum was reasonably consistent with a WD with a temperature of about 17,000K, but that an improved fit to the data at that time could be obtained with a combination of emission from a WD and an accretion disk.

Higher S/N spectra of VW Hyi in quiescence were obtained more recently with *FUSE*. With a practical wavelength range of 904-1188 Å, *FUSE* is sensitive to a second component, since the expected flux from a WD with a temperature of about 20,000 K is very different at 950 and 1100 Å. In addition, the *FUSE* spectral range and high spectral resolution allows the study of a broad range of line transitions. In the present work we only use one *FUSE* data set (B0700201), which presents only a small contribution from the second component. Since the second component is being studied elsewhere (Long 2007, private communication) using different *FUSE* data sets - E1140109, E1140112, E1140113), and it represents only a few percent of the flux, we neglect its contribution in the present work. In a previous work (Godon et al. 2004) we modeled the *FUSE* spectrum of VW Hyi, including a fast rotating hot accretion belt, and obtained a WD temperature of 23,000K. However in that work we did not deredden the spectrum, nor did we include the quasi-molecular satellite line in the modeling, and the *FUSE* spectrum was not combined with the STIS spectrum.

In the present analysis, we included the quasi-molecular lines in the synthetic spectral modeling, to fit the *FUSE* spectra better in the wavelength range  $\approx 1060 - 1080 \text{ Å}$ , and we dereddened the spectrum assuming  $E(B-V)=0.01$  (Bruch & Engel 1994). We are aware that because of the very low hydrogen column density one actually expects VW Hyi to have a zero reddening. However,

(i) such a small reddening value does not affect the results significantly, and (ii) we want to be consistent with the reddening values given in the literature and adopted in this work. The *FUSE* spectrum we used here was obtained 11 days after outburst, while there were three STIS spectra in the archive which we combined (weighting them by exposure time) to improve the S/N. Two short exposure STIS spectra were obtained 1 and 7 days after outburst; however, they are actually very similar to the long exposure STIS spectrum obtained 15 days after outburst. The *FUSE* and STIS spectra do match and fit well together.

Since the WD mass might be somewhere between  $\approx 0.6$  and  $0.9M_{\odot}$ , we computed models for two different values of  $\text{Log}(g)$ : 8.0 and 8.5. The model with  $\text{Log}(g) = 8.0$  was in better agreement with the distance of the system ( $\sim 60\text{pc}$ ) and gave a temperature of 22,000K, a projected rotational velocity of 400km/s and abundances as specified in Table 5. This model is shown in Figures 5 & 6. In both figures the *FUSE* and STIS spectra are binned at 0.1 Å, and the relative weight of the STIS spectrum is a little above twice that of the *FUSE* spectrum. Due to the excellent fit of the Si, C and N lines, we are confident that these abundances are accurate. While the model does not fit the flux (from a second component) in the short wavelengths of *FUSE*, it accurately follows the shape of the continuum and lines at wavelengths  $\lambda \sim 1050\text{\AA}$  all the way into the longer wavelengths of STIS.

The inclusion of the quasi-molecular opacity did improve the fit in the *FUSE* range 1055Å-1183Å, but did not change the fit in the STIS spectrum around  $\approx 1300 - 1400\text{\AA}$  range, because of the temperature of the model. The WD could be massive with  $\text{Log}(g) \sim 8.5$  or larger.

From this fit, it is evident that a WD alone is not enough to reproduce all the features of the spectrum. The bottoms of  $\text{Ly}\alpha$  &  $\text{Ly}\beta$  do not go to zero and indicate the presence of an additional component, which may or may not be linked to the broad emission features. As stated earlier, we do not intend in this paper to model the second FUV component of the system as this is being done elsewhere. We concentrate here on fitting the main continuum, the absorption lines, the quasi-molecular satellite lines and combining the *FUSE* spectrum with the STIS spectrum in order to assess the basic parameters of the WD: temperature, abundances, projected rotational velocity, and gravity. Our model neglects possible contribution from a quiescent (and optically thin) accretion disk. As an additional test we ran models for the fitting of the STIS spectrum alone and found complete agreement with the best fit model for the *FUSE*+STIS spectrum: a  $\text{Log}(g) = 8.0$  WD with a temperature  $T = 22,000\text{K}$  and a distance of 60pc, therefore confirming our result for the combined *FUSE*+STIS spectrum.

#### 4.4. EK Trianguli Australis

EK TrA is a poorly studied southern DN with an orbital period just above 1.3 hrs. It belongs to the SU UMa subclass (optical superhump was confirmed by Hassall (1985)) and has often been compared to the well studied DN VW Hyi because of their similarity. However, EK TrA has a much

longer outburst period than VW Hyi and can therefore easily be observed during deep quiescence for the study of its WD. Despite this, however, the mass of its WD is unknown and its distance is estimated to be  $d > 180\text{pc}$  from the non-detection of its secondary (Gänsicke et al. 1997). It is important to note that while Warner (1987) put it at 200pc, Hassall (1985) initially derived  $d \approx 68 - 86\text{pc}$ .

EK TrA was observed in August 1980 with IUE and 8 spectra were obtained with the SWP and LWR cameras covering mid-outburst and late decline from the outburst. The WD was revealed and contributed about 25% of the IUE SWP flux, with an accretion disk contributing the remaining 75% (Gänsicke et al. 1997). More recently, EK TrA was observed with *HST* 155 days after outburst and a high resolution STIS spectrum was obtained and analyzed by (Gänsicke et al. 2001). They confirmed the temperature of the WD found in Gänsicke et al. (1997) ( $T=18,800\text{K}$ ) assuming a canonical mass of  $0.6M_{\odot}$ , derived a rotational velocity of  $200\text{km s}^{-1}$  and slightly sub-solar abundances (0.5). They note that assuming a WD mass in the range  $0.3-1.4M_{\odot}$  leads to a temperature in the range 17,550-23,400K. More recently EK TrA was observed with *FUSE* 45 days after outburst and two 33ksec spectra were obtained with the same flux level as the existing STIS spectrum. The *FUSE* spectra have not been modeled previously, and we therefore decided to model EK TrA using the combined *FUSE*+STIS spectrum.

Since the WD mass of the system is basically unknown, we ran model fits for  $\text{Log}(g) = 7.5$ , 8.0, and 8.5 (corresponding to a mass of about 0.40, 0.65 and  $0.93M_{\odot}$  respectively) and obtained a WD temperature of 15,000, 17,000 and 18,000K respectively. The  $\text{Log}(g) = 8.0$  best fit model is presented in Figure 7. The broad emission lines (in blue/dark grey) have been masked for the fitting and both the *FUSE* and STIS spectra have been binned at  $0.175\text{\AA}$ . In Figure 8 we show the *FUSE* spectrum together with the best fit model shown in Figure 7. In the wavelengths  $\lambda < 1050\text{\AA}$  only the broad O VI doublet and the C III(977  $\text{\AA}$ ) emission lines are from the source, all the other sharp emission lines are due to air glow. The flux level at these wavelengths is of the same order as the noise and we do not attempt to model the spectrum there. In order to fit the line profiles in the *FUSE* range we had to set C=0.1 solar and Si=0.6 solar while keeping S and N to their solar values. Here also we found that the inclusion of the quasi-molecular satellite hydrogen line opacity improves the fit significantly, especially in the *FUSE* range where the flux suddenly drops shortward of the nitrogen absorption line at 1184  $\text{\AA}$ . In the STIS range this is not as pronounced but the drop in flux is also apparent shortward of the Si emission lines (1400 $\text{\AA}$ ). The distance we obtained is at most 137pc ( $\text{Log}(g) = 7.5$ ), somewhere between Hassall (1985) estimate and Warner (1987). The temperatures we obtained here are lower than Gänsicke et al. (1997). The differences between our result and Gänsicke et al. (1997) are probably due to the fact that, in their analysis, Gänsicke et al. (1997) did not include the opacity of the quasi-molecular satellite hydrogen lines, and they did not deredden the spectrum (it has  $E(B-V)=0.03$ ; Bruch & Engel (1994)). They interpreted the excess of flux in the longer wavelengths of STIS ( $>1,550\text{\AA}$ ) as possible emission from an optically thin accretion disk during quiescence, while we found, after dereddening the spectra, no evidence of flux excess. We note here that the complete absence of ISM molecular

hydrogen absorption lines in the *FUSE* spectrum of EK TrA suggests that the system might indeed be located rather nearby (say  $<150\text{pc}$ ). For comparison, in the present work, only the *FUSE* spectrum of VW Hyi at  $65\text{pc}$  shows such a complete absence, while SS Aur at  $200\text{pc}$  clearly shows some molecular hydrogen lines. We therefore speculate that the system is probably located at about  $125\text{pc}$ , as supported by our results.

#### 4.5. RU Pegasi

RU Peg is a U Gem type DN with an orbital period  $P_{orb} = 8.99$  hrs, a system inclination  $i = 33^\circ$ , a secondary spectral type K2-5V, and a primary (WD) mass  $M_{wd} = 1.29^{+0.16}_{-0.20} M_\odot$  (Stover 1981; Wade 1982; Shafter 1983). The near-Chandrasekhar mass for the WD has been corroborated by the Sodium ( $8190\text{\AA}$ ) doublet radial velocity study of Friend et al. (1990). They obtained a mass of  $1.24 M_\odot$  for the WD and also found very good agreement with the range of plausible inclinations, found in the study by Stover (1981). Recently, a Hubble FGS parallax of  $3.55 \pm 0.26$  mas was measured by Johnson et al. (2003) implying a distance of  $282\text{pc}$ .

Sion & Urban (2002) analyzed 4 IUE spectra of RU Peg obtained in deep quiescence, and found a WD temperature  $T_{eff} = 50 - 53,000\text{K}$  with a distance of  $\sim 250$  pc, assuming  $\text{Log}(g) = 8.7$  ( $M = 1.1 M_\odot$ ). More recently, a *FUSE* spectrum of RU Peg was obtained 60 days after outburst. The *FUSE* observation lasted for a little more than 3000s (raw exposure time). From all the 5 systems in this analysis, RU Peg is the most affected by ISM absorption lines. We show the *FUSE* spectrum of RU Peg with line identifications in Figure 9, where we have marked only the most prominent molecular hydrogen lines. Two modelings have been carried out (Sion et al. 2004a; Urban & Sion 2006) for the *FUSE* spectrum of RU Peg; and both found a WD temperature similar to Sion & Urban (2002) assuming  $M_{wd} = 1.2 M_\odot$ .

While we are confident that the WD in RU Peg is actually massive and that its temperature is very large ( $>50,000\text{K}$ ), the *FUSE* spectrum has never been modeled in detail as many of the ISM molecular hydrogen lines were misidentified. In addition, since this *FUSE* analysis was carried out, CALFUSE has been updated and we are making use of this implementation. For RU Peg, we decided to also model the ISM molecular and atomic hydrogen absorption lines to help improve the model fit.

In Figure 10 we show the best-fit model to the *FUSE* spectrum of RU Peg (binned at  $0.1\text{\AA}$ ). This model consists of a synthetic WD spectrum model multiplied by the transmission values obtained from the ISM model. This WD model has a temperature of  $70,000\text{K}$ , a rotational velocity of  $40\text{km/s}$ ,  $\text{Log}(g) = 8.8$ , subsolar carbon and silicon abundances and supra solar nitrogen and sulfur abundances as follows. The silicon abundance was set to 0.2 times solar to match the Si IV ( $1066\text{\AA}$ ) line. The nitrogen abundance was set to solar to match the N III ( $980$ ,  $1183$ , &  $1184.5\text{\AA}$ ) lines. The carbon abundance was set to 0.2 times solar to match the feature at  $1108\text{\AA}$  and the flat portion of the spectrum at  $1160-1170\text{\AA}$ . The sulfur abundance was set to 10 times solar

to match the strong absorption of the S VI and S IV lines. It is worth noting that if the N/C ratio is anomalous in the WD photosphere then this would imply recent thermonuclear processing in the WD, because the disk emission lines do not indicate a N/C ratio larger than one, but rather the opposite (Sion & Urban 2002). However, our abundances determination is not robust because the nitrogen and carbon absorption lines are affected by broad emission lines and ISM molecular hydrogen absorption lines.

The projected rotational velocity was found by matching the profile of the carbon, oxygen, silicon and sulfur lines, and in particular the square-shaped bottom of the C III 1175Å absorption feature. The ISM model (in Figure 10) has zero metallicity, a temperature of 100K, a turbulent velocity of  $b=30\text{km s}^{-1}$ , a molecular hydrogen column density of  $1 \times 10^{16}\text{cm}^{-2}$  and an atomic hydrogen column density of  $1 \times 10^{17}\text{cm}^{-2}$ . This ISM model fits best the stronger (molecular hydrogen) absorption lines but does fit the sharper and weaker (molecular hydrogen) absorption lines.

It is worth noting that all the synthetic WD spectra we generate between  $T \sim 50,000\text{K}$  up to  $T \sim 80,000\text{K}$  (with an approximate NLTE line treatment option switched on in SYNSPEC and using LTE stellar atmosphere models from TLUSTY) fit the data similarly, the main difference is the radius (and therefore mass and gravity) of the WD which is fixed by scaling the model to the data assuming a distance of 282pc. Consequently, the 50,000K model had  $\text{Log}(g) = 8.55$ , while the 70,000K model had  $\text{Log}(g) = 8.8$ . In order to agree with a mass of  $1.29M_{\odot}$  we ran models with  $\text{Log}(g) = 9.23$  with increasing temperatures and found that the model that agrees with the distance of 282pc has a temperature of 110,000K. At such a high temperature the S IV, Si IV and O IV lines between 1060Å and 1080Å are not deep enough to match the observed features. In addition, since we performed only the simplest NLTE approximation, and also obtained  $\chi^2 = 0.827$  (against 0.539 for the  $T=70,000\text{K}$  model), we decided not to chose the 110,000K model as a best fit model.

On the other hand, at 50,000K, the O IV line and the nominally strong N IV and S VI lines are not pronounced. The temperature had to be increased to 70,000K to clearly show the appearance of these lines in the synthetic spectrum (including the O IV line at 1067.8Å). Therefore, we chose the 70,000K model as our best fit model.

However, the Si IV and O IV lines (between 1066 and 1068 Å) are contaminated by sharp ISM absorption lines from molecular hydrogen (L3P2 1066.90Å, & L3R3 1067.48Å) and the Ar I 1066.66Å line (the other argon line Ar I 1048.20Å is also present). However, these sharp ISM lines were not modeled accurately in the ISM model presented in Figure 10. Consequently, in order to fit the sharper absorption lines of the ISM we generated a second ISM model. This model fits the sharp lines better but does not fit the stronger lines as well (it is likely that the ISM has more than one component). The second ISM model has zero metallicity, a temperature of 300K, a turbulent velocity of  $b=10\text{km s}^{-1}$ , a molecular hydrogen column density of  $1 \times 10^{16}\text{cm}^{-2}$  and an atomic hydrogen column density of  $1 \times 10^{18}\text{cm}^{-2}$  and a blueshift velocity of  $-35\text{km s}^{-1}$ . In Figure 11 we present the 70,000K WD synthetic spectrum including the second ISM model in the region 1060Å

- 1080Å . From this model we see that the O IV line is distinct from the molecular hydrogen line (L3R3) but it is not very strong. As for the Si IV lines, they are contaminated by argon and a molecular hydrogen line (L3P2). Since argon (and iron, and all the metals) is not included in the ISM model, we cannot confirm whether the Si IV line is present. We also note that S IV is shifted to the red compared to the WD model. Indeed, a close look at all the lines from the system reveals that some of the (broader) lines are shifted by as much as 0.5Å to the red; this is especially the case for the S VI, O VI, S IV and C III lines. This could be due to the motion of the WD in the binary, as the red shift is close to the maximum radial velocity shift of the WD in the system and the *FUSE* spectrum had a duration much shorter than the binary period. It is possible that these strong absorption lines do not form in the stellar photosphere, but possibly in a corona above it or in a hot boundary layer in front of it. This can be determined only if we have line velocities in phase-resolved FUV spectra to compare with the velocity derived for photospheric lines in the white dwarf's rest frame.

#### 4.6. The Quasi-Molecular Satellite Lines

One of the improvements we made in the present work is the modeling of the quasi-molecular satellite lines of hydrogen in the *FUSE* spectra of VW Hyi and EK TrA. Such modeling has been carried out previously for CV WDs such as WZ Sge (Sion et al. 1995a) and AM Her (Gänsicke et al. 2006), and also for DA WDs (Koester et al. 1996, 1998; Dupuis et al. 2003, 2006) and ZZ Ceti WDs (Allard et al. 2004b). It is interesting to compare our results with these results as the presence/absence of the quasi-molecular hydrogen lines in FUV spectra of WDs is not yet fully understood. Quasi-molecular satellite transitions take place during close collisions of the radiating hydrogen atom with a perturbing atom or proton. These absorption features are present in the red wings of the Lyman series lines ( $\text{Ly}\alpha$  in STIS and IUE spectral ranges at 1400 & 1600Å ;  $\text{Ly}\beta$  at 1058 & 1076Å and  $\text{Ly}\gamma$  around 995Å - in the *FUSE* spectral range) and provide a noticeable source of opacity in the hydrogen-rich atmosphere of WDs (Koester et al. 1985; Allard et al. 1994, 1998, 2004a,b; Dupuis et al. 2006). In theory the  $\text{H}_2^+$  satellite appearance is very sensitive to the degree of ionization and may be used as a temperature diagnostic. On the other hand, since the quasi-molecular opacity is proportional to the proton and H I densities, the quasi-molecular satellite lines are expected to be observed at higher effective temperatures in WDs with larger surface gravities (Koester et al. 1996; Dupuis et al. 2003). We summarize in Table 6 the occurrence of the quasi-molecular satellite lines in a number of WDs, covering a wide range of temperatures and gravities, listed in order of increasing temperature. We are aware that these WDs belong to different types (CVs, DA and ZZ Ceti) and that the detection of the quasi-molecular satellite line also depends on the S/N of the data. However, this table might help put restrictions on the upper and lower limits of the gravity and temperature of WDs, especially when the mass and distance are relatively unknown. For example it is clear that the WD of EY Cyg must have  $\text{Log}(g) < 9.3$ , otherwise one would expect to see the quasi-molecular satellite lines in the *FUSE* range. For WW Cet the opposite is true and one can therefore expect  $\text{Log}(g) > 7.8$ . In fact one could argue that for WW Cet

$\text{Log}(g) > 8.3$  while for EY Cyg  $\text{Log}(g) < 9.0$ , as this would be even more consistent with Table 6 and with the errors on the WD masses of these systems. However, the system that really stands out in the list is AM Her which exhibits the 1076Å feature but not the one at 1058Å. Gänsicke et al. (2006) suggest that the magnetic field plays a role in the formation of these lines, and cite the fact the magnetic DA WD PG 1658+441 has a weaker than expected 1058Å  $H_2^+$  absorption feature. However, Dupuis et al. (2003) mentioned that the treatment of the quasi-molecular satellite opacities could be improved, especially in the range of ionic densities encountered in the atmosphere of ultramassive WDs. The *FUSE* spectrum of PG 1658+441 actually shows that both the 1058Å and 1076Å absorption features are rather weak, contrary to AM Her where the 1058Å feature is completely absent. We see the importance of generating a large database of WDs exhibiting the quasi-molecular satellite lines of hydrogen, as it could be used to assess the WD’s temperature and/or gravity more accurately.

## 5. Summary

We have analyzed the FUV spectra of five DNs in quiescence with the aim of securing more accurate values of system parameters, such as the WD surface temperatures  $T_{eff}$ , their projected rotational velocities  $V_{rot} \sin i$  (derived mainly from the *FUSE* data), their chemical abundances, their surface gravities and the distances to the systems. Four of these systems (EY CYG, SS Aur, VW Hyi, and EK TrA) were part of our broader *HST* archival program with matching *FUSE* and *HST*/STIS spectra, while RU Peg has only one *FUSE* spectrum. We carried out the analysis including options for the treatment of the hydrogen molecular satellite lines (for modeling cooler WDs) and NLTE atmosphere models (for modeling hotter WDs), dereddening the spectra and identifying the ISM molecular absorption lines in the *FUSE* spectra. The following improvements (in methods and results) were achieved.

For EY Cyg, we disregarded the noisy portion of the *FUSE* spectrum ( $\lambda < 950\text{\AA}$ ), which turned out to be an artifact of the re-processing and thus improved the fit. From the combined *HST*/STIS + *FUSE* spectrum we found  $T_{eff} = 30,000\text{K}$  and  $d=530\text{pc}$  assuming  $\text{Log}(g) = 9$ ; and  $T_{eff} = 32,000\text{K}$  and  $d=310\text{pc}$  assuming  $\text{Log}(g) = 9.5$ . We derived for the first time evidence of CNO processing in the photosphere of the WD itself in EY Cyg. Previously, only the emission line strengths implied suprasolar N and subsolar (deficient) C. Therefore EY Cyg’s WD is only the third WD known to have anomalous N/C in its photosphere, the other objects being VW Hyi and U Gem.

For SS Aur, we re-evaluated and improved the WD parameters by modeling for the first time for this object the combined *FUSE*+STIS spectra. We improved the fitting in the *FUSE* short wavelength range without the need to introduce a second component, contrary to (Sion et al. 2004a)’s result where the second component actually gave too much flux. This might be due to the fact that Sion et al. (2004a) did not deredden the *FUSE* spectrum of SS Aur, while we assumed  $E(B-V)=0.08$ . In addition this result is in excellent agreement with the distance and we found no

deficiency in carbon. We also improved the line identifications over the previously published *FUSE* analysis.

For VW Hyi, the *FUSE* and STIS spectra were combined together for the first time. The opacity of the quasi-molecular satellite lines of hydrogen were included, and the spectrum was dereddened assuming  $E(B-V)=0.01$ . Our best model fit has  $T_{eff}=22,000K$ ,  $Log(g) = 8.0$  and  $d = 60pc$ . Both the projected rotational velocity (400km/s) and the chemical abundances are determined quite accurately due to the high S/N of the *FUSE* spectrum. We find a ratio  $C/N=0.25/3=1/12$  and the silicon abundance is almost twice solar. A second component is detected in the very short wavelengths contributing only a few percent of the total flux. Even though we deliberately decided not to model the second component, our results are in complete agreement with all the results from previous analyses of the system (Mateo & Szkody 1984; Sion et al. 1995a; Gänsicke & Beuermann 1996; Sion et al. 1996, 1997, 2001; Godon et al. 2004).

For EK TrA we re-evaluated and improved the WD parameters by modeling for the first time the combined *FUSE*+STIS spectrum. We found a WD temperature of  $17,000K \pm 1,000K$  assuming  $Log(g) = 8.0 \pm 0.5$  leading to a distance of  $\approx 125pc$ . Gänsicke et al. (2001) carried out a similar analysis, but found a somewhat higher temperature and a flux excess in the longer wavelengths, assuming a distance  $d > 180pc$ . The difference in results is probably due to our different modeling; namely we combined the *FUSE* and STIS spectra, included the opacity of the quasi-molecular satellite lines for hydrogen, and dereddened the spectrum.

For RU Peg we improved the line identifications over the previously published *FUSE* analysis and we show that the large mass of the WD gives a better agreement with a higher temperature than previously estimated; namely the  $Log(g) = 8.8$  model gives a temperature of 70,000K for a distance of 282pc. We find that the projected rotational velocity is rather small ( $< 70km/s$ ) and the carbon and silicon abundances are sub-solar; while sulfur and nitrogen are over-abundant. We assessed the molecular hydrogen column density ( $N(H_2) = 1 \times 10^{16}cm^{-2}$ ), the atomic hydrogen column density ( $N(HI) = 1 \times 10^{17} - 1 \times 10^{18}cm^{-2}$ ), and found that the lines are blue shifted with a velocity of  $-35km s^{-1}$ .

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Table 1: Parameters of the Systems

Name	Type	$E_{B-V}$	d (pc)	$P_{orb}$ (hrs)	$i$ (deg)	Spectral Type	$M_1$ ( $M_\odot$ )	$M_2$ ( $M_\odot$ )	$V_{max}$	$V_{min}$
EY Cyg	DN UG	0.00	450	11.02377	$16 \pm 1$	K7 V	$1.26 \pm 0.29$	$0.59 \pm 0.13$	11.4	15.5
SS Aur	DN UG	0.08	200	4.3872	$38 \pm 16$	M1 V	$1.08 \pm 0.40$	$0.39 \pm 0.02$	10.5	14.5
VW Hyi	DN SU	0.01	65	1.783	$60 \pm 10$	L0	$0.63 - 0.86$	$0.11 \pm 0.02$	8.5	13.8
EK TrA	DN SU	0.03	180	1.5091	$58 \pm 7$		$0.46 \pm 0.10$	$0.09 \pm 0.02$	12.0	17.0
RU Peg	DN UG	0.00	282	8.9904	$33 \pm 5$	K2-5V	$1.29 \pm 0.20$	$0.94 \pm 0.04$	9.0	13.1

References. EY Cyg: Sarna et al. (1995); Smith et al. (1997); Costero et al. (1998); Tovmassian et al. (2002); Costero et al. (2004); Sion et al. (2004b); SS Aur: Shafter (1983); Shafter & Harkness (1986); Harrison et al. (1999); VW Hyi: Schoembs & Vogt (1981); van Amerongen et al. (1987a,b); Sion et al. (1995b); Huang et al. (1996b); Long et al. (1996); Wheatley et al. (1996); Sion et al. (1997); EK TrA: Vogt & Semeniuk (1980); Warner (1987); Gänsicke et al. (1997, 2001); RU Peg: Stover (1981); Wade (1982); Shafter (1983); Friend et al. (1990); Johnson et al. (2003). The E(B-V) values are from Verbunt (1987); La Dous (1991); Bruch & Engel (1994).

Table 2: FUV Observations of the Systems: *HST* & *FUSE* Spectra

System	Date (dd/mm/yy)	Telescope /Instrument	Exp time (ksec)	Dataset	Filter/Grating /Aperture	Operation Mode	$\tau_q^a$ (days)
EY Cyg	16-07-03	FUSE	18	D1450101	LWRS	TTAG	dq <sup>b</sup>
	10-02-03	STIS	0.7	O6LI0V010	G140L/52X0.2	ACCUM	dq <sup>b</sup>
SS Aur	13-02-02	FUSE	14.5	C1100201	LWRS	TTAG	28
	20-03-03	STIS	0.6	O6LI0F010	G140L/52X0.2	ACCUM	30
VW Hyi	18-08-01	FUSE	18	B0700201	LWRS	TTAG	11
	01-06-00	STIS	2.5	O5E205010	E140M/0.2X0.2	ACCUM	1
	06-06-00	STIS	2.5	O5E206010	E140M/0.2X0.2	ACCUM	7
	10-12-01	STIS	9.1	O5E201010	E140M/0.2X0.2	ACCUM	15
EK TrA	24-06-02	FUSE	33	Z9104301	LWRS	TTAG	45
	24-06-02	FUSE	33	Z9104302	LWRS	TTAG	45
	25-07-99	STIS	4.3	O5B612010	E140M/0.2X0.2	TTAG	155
RU Peg	05-07-02	FUSE	2.9	C1100101	LWRS	TTAG	60

<sup>a</sup>in the last column  $\tau_q$  is the time in quiescence, i.e. since outburst

<sup>b</sup>for the very long recurrence time systems (EY Cyg & BZ UMa), the observations were made in deep quiescence (dq)



Table 3: *FUSE* Lines

Line Identification	Wavelength (Å)	Origin	EY Cyg	SS Aur	VW Hyi	EK TrA	RU Peg
H I		c,ism	e,c	e,c	e,c	e,c	e,c
O I		c,ism	e,c	-	-	e,c	-
N IV	921.5-924.9	s	e,c	-	-	-	a
S VI	933.5	s	-	-	-	-	a
S VI	944.5	s	-	-	-	-	a
C III	977.0	s	-	e	e	e	e
N III	979.8	s	-	-	-	-	a
N III	991.6	s	c	c	-	-	c
C II	1010.	s	-	a	-	-	-
Si II	1020.7	ism	-	a	-	-	-
O VI	1031.9	s	e	e	e	e	a,e
	1037.6	s	e	c	e	e	a,e
C II	1036.3	ism	a	-	a	a	-
S IV	1062.6	s	-	c	-	-	a
C II	1066.	s	-	a	a	-	-
Si IV	1066.6	s	-	-	-	-	a
O IV	1067.8	s	-	-	-	-	a
S IV	1073.0,1073.5	s	a	a	-	-	a
N II	1084.0-1085.7	s,c,ism	c	c	a	c	c
Si III	1108.4-1113.2	s	-	-	a	a	-
C III	1125.6	s	a	-	-	a	-
C II	1127	s	-	-	-	a	-
Si IV	1122.5	s	a	a	a	a	a
	1128.3	s	a	a	a	a	a
N I	1134.2-1135.0	s,c,ism	c	c	c	c	c
Si III	1140.5-1145.7	s	a	a	a	-	-
Si III	1158.1	s	-	-	-	a	-
He II	1168.6	c	e,c	-	e,c	e,c	e,c
C III	1174.9-1176.4	s	-	-	a	e,a	e,a

The following abbreviations have been used: a - for absorption; e - for emission; c - for contamination (e.g. air glow); s - for source; and ism - for interstellar medium.

Table 4: STIS Lines

Line Identification	Wavelength (Å)	Origin	EY Cyg	SS Aur	VW Hyi	EK TrA
C III	1174.9-1176.4		-	-	a	e
Si II	1190.4		a,e?	-	-	e?
	1193.3		a,e?	-	-	e?
	1194.5		a,e?	-	-	e?
Si III	1206.5		e	e	-	e
H I	1215.7		a,c	a	a,e,c	a,c
N V	1238.8		e	e	-	e
	1242.8		e	e	-	e
Si II	1259.9, 1260.4		-	a	a	a
	1264.7, 1265.0		-	a?	a	a
C I	1266.4		a?	-	a	-
Si III	1298.9		a	a	a	a?
Si II	1304.4		a	-	a	a?
N I	1316.0		-	-	-	-
	1319.7		-	-	-	-
C I	1328.8, 1329.6		-	-	a	-
C II	1334.5, 1335.7		a	a,e?	a	-
C I+	≈1350		-	-	a	a,e
Si IV	1393.8		e	a,e?	e,a?	e
	1402.8		e	a,e?	e,a?	e
Ni II	1467.3, 1467.7		-	-	-	-
S I	1485.6, 1487.2		-	-	a	-
N I	1492.6, 1492.8		-	-	a	-
	1494.7		-	-	a	-
Si II	1526.7		-	-	a	a
	1533.4		-	-	a	a
C IV	1548.2		-	e	e	e
	1550.8		-	e	e	e
C I	1560.3-1561.4		-	-	a	-
He II	1640.5		e	-	-	e
C I	1656.3-1658.1		-	-	a?	a
Al II	1670.8		-	-	a?	a

The following abbreviations have been used: a - for absorption; e - for emission; c - for contamination (e.g. air glow); s - for source; and ism - for interstellar medium.

Table 5: Synthetic Stellar Spectra

Name	$Log(g)$ (cm s <sup>-2</sup> )	T (10 <sup>3</sup> K)	$V_{rot}sin(i)$ (km s <sup>-1</sup> )	[C] Solar	[Si] Solar	[N] Solar	[S] Solar	d (pc)	f <sup>a</sup>	$\chi^2_\nu$	Figure
EY Cyg	9.00	30.0±2.0	100±50	0.03±0.02	0.6±0.1	2.0 ±1.0	6.0±1.0	530±60	1.50	1.140	1,2
	9.50	32.0±2.0	100±50	0.03±0.02	0.6±0.1	2.0 ±1.0	6.0±1.0	310±40	1.50	1.046	-
SS Aur	8.31	27.0±1.0	400±100	1.0	1.0	1.0	1.0	200	0.93	1.476	-
	8.31	30.0±1.0	400±100	1.0	1.0	1.0	1.0	254	0.93	1.472	-
	8.71	31.0±1.0	400±100	1.0	1.0	1.0	1.0	200	0.93	1.474	-
	8.71	33.0±1.0	400±100	1.0	1.0	1.0	1.0	240	0.93	1.472	-
	8.93	34.0±1.0	400±100	1.0	1.0	1.0	1.0	200	0.93	1.471	3,4
VW Hyi	8.00	22.0±1.0	400±100	0.25±0.05	1.8±0.2	3.0±1.0	1.0	60	1.00	0.734	5,6
	8.50	24.0±1.0	400±100	0.25±0.05	1.8±0.2	3.0±1.0	1.0	51	1.00	0.770	-
EK TrA	7.50	15.5±0.5	200±100	0.1±0.05	0.6±0.1	1.0	1.0	137	1.00	0.781	-
	8.00	17.0±0.5	200±100	0.1±0.05	0.6±0.1	1.0	1.0	126	1.00	0.781	7,8
	8.50	18.0±0.5	200±100	0.1±0.05	0.6±0.1	1.0	1.0	104	1.00	0.780	-
RU Peg	8.55	50.0±2.0	40/-15+30	0.2±0.1	0.2±0.1	≥1.0	10±5	282	–	0.565	-
	8.72	60.0±5.0	40/-15+30	0.2±0.1	0.2±0.1	≥1.0	10±5	282	–	0.545	-
	8.80	70.0±5.0	40/-15+30	0.2±0.1	0.2±0.1	≥1.0	10±5	282	–	0.539	10,11
	8.92	80.0±5.0	40/-15+30	0.2±0.1	0.2±0.1	≥1.0	10±5	282	–	0.553	-
	9.23	110.0±5.0	40/-15+30	0.2±0.1	0.2±0.1	≥1.0	10±5	282	–	0.827	-

<sup>a</sup>The factor by which the STIS spectrum had to be scaled so that its flux level (continuum) matches the flux level (continuum) of the corresponding *FUSE* spectrum at the overlapping wavelengths  $\approx 1150 - 1185\text{\AA}$

Table 6: Presence of Quasi-Molecular Satellite Lines ( $H_2^+$ ) in White Dwarfs

Name	type	$T_{eff}$ (1000K)	$Log(g)$	FUSE range 1058,1076Å	STIS range 1,400Å
G226-29	ZZ Ceti	12.0	7.93	yes, yes	-
G185-32	ZZ Ceti	12.0	7.9	yes, yes	-
WZ Sge	DN UG	14.0	8.5	-	yes
WZ Sge	DN UG	15.5	8.5	-	weak
40 Eri B	DA WD	16.5	7.77	yes, yes	-
EK TrA	DN SU	17.0	8.0	yes, yes	weak
BZ UMa	DN SU	17.5	8.5	-	yes
AM Her	NL AM	19.8	8.2	no, yes	very weak
Wolf 1346	DA WD	19.9	7.84	yes, yes	-
He 3	DA WD	21.4	8.04	yes, yes	-
GD 140	DA WD	21.6	8.41	yes, yes	-
VW Hyi	DN SU	22.0	8.0	yes, yes	no
WZ Sge	DN UG	23.2	8.5	yes, yes	-
L825-14	DA WD	25.0	7.76	no, no	-
WW Cet	DN UG	26.0	8.3	yes, yes	no
PG 1658+441	DA WD	29.6	9.31	weak, yes	-
EY Cyg	DN UG	30.0	9.0	no, no	no

References. G226-29 & G185-32: Allard et al. (2004b); BZ UMa: based on an inspection of the STIS spectrum compared to a synthetic spectrum; EK TrA: this work; AM Her: Gänsicke et al. (2006); VW Hyi: this work; WW Cet: the quasi-molecular feature was detected but not modeled in Godon et al. (2006b); PG 1685+441: Dupuis et al. (2003, 2006); all the other DA WDs are from the ORFEUS observations of Koester et al. (1998). WZ Sge: all the modelings carried out in Sion et al. (1995a); Godon et al. (2006a); Long et al. (2003) assumed a 0.9 solar mass. The 2004 July STIS spectrum of WZ Sge (with  $T_{eff}=15,500K$ ) was analyzed again in the present work to detect the quasi-molecular hydrogen feature around 1400Å : it was found to be rather weak.

## FIGURE CAPTIONS

Fig. 1.—

The combined *FUSE*+STIS spectrum of EY Cyg (light grey/red line) is shown together with a 30,000K single WD model (thick black line) assuming  $\text{Log}(g) = 9.0$ . The regions masked during fitting are shown in blue (dark grey). With a flux of only a few  $10^{-15} \text{ergs s}^{-1} \text{cm}^{-2} \text{\AA}^{-1}$ , EY Cyg is a relatively weak source contaminated with many air glow emission lines in the *FUSE* range, especially in the shorter wavelength. The increase of flux at  $\lambda < 934 \text{\AA}$  is masked in the modeling (see text). The WD model has a projected rotational velocity of  $100 \text{km s}^{-1}$ , a very low carbon abundance (note the absence of the C III (977Å) and C IV (1550Å) emission lines) and  $\chi^2_\nu = 1.108$ . The distance obtained from fitting the fluxes is  $\approx 500 \text{pc}$ .

Fig. 2.— The 30,000K WD model (from Fig.1) is shown here with the *FUSE* spectra of EY Cyg (binned here at  $0.1 \text{\AA}$ ) and line identifications. Air glow lines are annotated with a plus sign inside a circle; the O I, N I and N II emission lines are also due to air glow; the interstellar H<sub>2</sub> molecular lines have been labeled vertically; the O VI doublet emission is from the source; – all these emission lines together with the ISM molecular hydrogen absorption lines have been masked in the fitting. The abundance of C, S, N and Si have been set to 0.03, 6.0, 2.0 and 0.6 solar (respectively) by fitting the following absorption lines: S IV (1173Å), C II (1010Å, 1066Å), C III (1175Å), Si III (1140-1145Å) and N II (1184-1186 Å).

Fig. 3.— The combined *FUSE*+STIS spectrum of SS Aur (in red/light grey) together with the best fit WD model (in black). The regions that have been masked for the fitting are shown in blue (dark grey). The synthetic stellar spectrum has a temperature of 34,000K (assuming  $\text{Log}(g) = 8.93$  and a distance of 200pc), a projected rotational velocity of  $400 \text{km s}^{-1}$  and solar abundances. The spectrum has been dereddened assuming  $E(B-V)=0.08$ .

Fig. 4.— The *FUSE* spectrum of SS Aur (binned here at  $0.1 \text{\AA}$ ) is shown with the best fit model shown in Figure 3. Note that the C III (977 Å) emission indicates that there could possibly be some emission at 1175Å, which would make it difficult to detect absorption there, potentially explaining the observed flat spectrum in that region. For that reason the carbon abundance was fitted using the C II lines seen in absorption both at 1010 Å and 1066 Å. The sharp emission lines due to air glow and the ISM molecular hydrogen absorption lines have been masked for the fitting.

Fig. 5.— The combined *FUSE*+STIS spectrum of VW Hyi is shown in red (light grey) together with the best fit WD model (in black). The emission lines that have been masked are shown in blue (dark grey). The synthetic stellar spectrum has a temperature  $T = 22,000 \text{K}$  (assuming  $\text{Log}(g) = 8.0$ ), a projected rotational velocity of  $V_{\text{rot}} \sin(i) = 400 \text{km s}^{-1}$ , and non-solar composition: C=0.25×solar, Si=1.8×solar, N=3.0×solar. The spectrum has been dereddened assuming  $E(B-V)=0.01$  and the distance obtained from the fitting is 60pc.

Fig. 6.— The *FUSE* portion of Figure 6 is shown with line identifications. The dotted-dashed line shows the same model without the inclusion of the quasi-molecular satellite lines at 1058Å and

1076Å (shown with arrows). The synthetic spectrum does not attempt to model the O VI doublet and C III (977Å) emission lines and the low-level flux flat continuum in the lower wavelengths.

Fig. 7.— The combined *FUSE*+STIS spectrum of EK TrA is shown in red (light grey) together with the best fit WD model (in black). The strong emission lines that have been masked for the fitting are shown in blue (dark grey). The synthetic stellar spectrum has a temperature  $T = 17,000\text{K}$  (assuming  $\text{Log}(g) = 8.0$ ), a projected rotational velocity of  $200\text{km s}^{-1}$ , and the following abundances (in solar units):  $\text{C}=0.1$  and  $\text{Si}=0.6$ . The spectrum was dereddened assuming  $E(B-V)=0.03$  and the distance obtained from the fitting is  $d=126\text{pc}$ .

Fig. 8.— The *FUSE* spectrum of EK Tra (in red/light grey) is shown with the best fit model presented in Figure 6 and line identifications. The dotted-dashed line shows the same model without the inclusion of the quasi-molecular satellite lines modeling, at  $1058\text{\AA}$  and  $1076\text{\AA}$ . With a flux of  $\approx 1 \times 10^{-14}\text{ergs s}^{-1}\text{cm}^{-2}\text{\AA}^{-1}$  and less, EK TrA is actually a weak *FUSE* source. All the sharp emission lines are due to contamination (helio- and geo-coronal emission) and have been masked for the fitting. The broad C III ( $977\text{\AA}$  &  $1175\text{\AA}$ ) and O VI ( $\sim 1130 - 1140\text{\AA}$ ) emission lines are associated with the source. The synthetic spectrum does not attempt to model the O VI doublet and C III emission lines and the low-level flux flat continuum in the lower wavelengths (which is of the level of the noise). The C II ( $1036\text{\AA}$ ) absorption line is interstellar.

Fig. 9.— The *FUSE* spectrum of RU Peg in quiescence. The sharp ISM molecular hydrogen absorption lines have been annotated as in Figure 2. The very broad emission lines of the OVI doublet and CIII ( $977$  &  $1175$  Å) are clearly apparent. In addition there are absorption lines which originate only at very high temperatures ( $T \geq 50,000\text{K}$ ) such as N IV (around  $923\text{\AA}$ ), S VI ( $933.5$  &  $944.5\text{\AA}$ ), and O VI ( $1031.7$  &  $1037.3\text{\AA}$ ). The additional sharp absorption lines (from low ionization levels such as N I) are either from the ISM or due to air contamination (or both). Though the flux is  $\approx 1 \times 10^{-13}\text{ergs s}^{-1}\text{cm}^{-2} \text{\AA}^{-1}$ , the spectrum is clearly under-exposed (1ksec) and has a low S/N.

Fig. 10.— The best fit WD model to the *FUSE* spectrum of RU Peg is shown in this Figure. The synthetic spectrum is in solid black, the observed spectrum is in red (light grey), the regions of the observed spectrum masked for the fitting are shown in blue (dark grey). The synthetic stellar spectrum consists of  $70,000\text{K}$  WD, with a projected rotational velocity of  $40\text{km s}^{-1}$ , carbon abundance of 0.2 times solar, silicon abundance of 0.2 times solar, and sulfur abundance of 10 times solar. The absorption lines that have been used to produce the abundance fits are annotated.

Fig. 11.— A detail of the fitting of the absorption lines around  $1070\text{\AA}$  (note the Y-axis scale!). The molecular hydrogen lines have been marked below the spectrum for clarity. The absorption lines shown are S IV ( $1062.7\text{\AA}$ ), Si IV ( $1066.6\text{\AA}$ ), O IV ( $1067.8\text{\AA}$ ), and the S IV doublet (around  $1073.5\text{\AA}$ ). The ISM model does not include metals and therefore the Ar I and Fe II lines are not modeled, though they are present in the observed spectrum. Note the redshift of the S IV doublet.

























